COMBINATIONS OF EARTH ORIENTATION MEASUREMENTS: COMB94 AND POLE94

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ABSTRACT

A Kalman filter has been used to combine Earth orientation measurements taken by optical astrometry with SPACE94, a previously determined combination of Earth orientation measurements taken by space-geodetic techniques, Prior to their combination with SPACE94, the bias, rate and annual term of the optical astrometric series were corrected, the stated uncertainties of the measurements were adjusted, and data points considered to be outliers were deleted. The adjusted optical astromctric series were then combined with SPACE94 in two steps: (1) the Bureau International de l'Heure (BIH) optical astrometric series was combined with SPACE94 to form COMB94, a combined series of smoothed, interpolated polar motion and UT1 –UTC values spanning January 20.0, 1962 to January 27.0, 1995 at 5-day intervals, and (2) the International Latitude Service (ILS) optical astrometric series was combined with COMB94 to form POLE94, a combined series of smoothed, interpolated polar motion values spanning January 20, 1900 to January 21, 1995 at 30,4375-day intervals.

INTRODUCTION

The Kalman Earth Orientation Filter (KEOF) developed at the Jet Propulsion Laboratory [JPL; *Eubanks, 1988; Morabito et al.*, 1988; *Freedman et al.*, 1994] has been used to combine independent measurements of the Earth's orientation taken by optical astrometry with those taken by the modern, space-geodetic techniques of lunar laser ranging (LLR), satellite laser ranging (SLR), very long baseline interferometry (VLBI), and the global positioning system (GPS). Changes in the Earth's orientation have been under observation by optical astrometry since the late 19th century, whereas the space-geodetic observations span only about two decades. Thus, the optical astrometric observations arc a valuable resource for: (1) investigating Earth orientation changes that occurred prior to the start of the more accurate space-geodetic measurements, and (2) investigating decadal-scale changes in the Earth's orientation (for reviews of Earth rotation studies *see, e. g., Munk and MacDonald,* 1960; *Lambeck*, 1980, 1988; *Hide and Dickey,* 1991; *Eubanks,* 1993; *Rosen, 1993),* Combining the optical astrometric with the space-geodetic measurements enables such investigations by providing investigators with an observed Earth orientation series that, by incorporating all available independently determined measurements, has the highest possible data density and spans the greatest possible length of time.

Prior to incorporating the optical astrometric measurements, the space-geodetic measurements were first combined to form SPACE94 [Gross, A combination of Earth orientation measurements: SPACE94, this volume, 1995]. The incorporation of the optical astrometric measurements was then done in two steps: (1) the optical astrometric polar motion and UT1 determinations of *Li [1985] were* combined with the space-geodetic measurements comprising SPACE94 to form COMB94, and (2) the International Latitude Service (11.S) optical astrometric polar motion series [*Yumi and Yokoyama*, 1980] was combined with the independent optical astrometric and space-geodetic measurements comprising COMB94 to form POLE94.

GI3NERATION OF COMB94

The particular optical astrometric polar motion and UT1 series used in generating COMB94 was that determined at the Bureau International de l'Heure (BIH) from an analysis of time and latitude observations *[Li, 1985; Li and Feissel*, 1986]. This BIH optical astrometric series, consisting of values for UT1 and the x- and y-components of polar motion (PMX and PMY, respectively) spanning 1962.0 –1982.0 at 5-day intervals, was combined with the space-geodetic series comprising SPACE94 after first: (1) correcting the BIH series to have the same bias, rate, and annual term as the space-geodetic series comprising SPACE94, (2) applying a constant multiplicative scale factor to the measurement uncertainties of the BIH series so that its residual, when differenced with SPACE94, had a reduced chi-square of one, and (3) deleting those data points whose residual values were greater than three times their adjusted uncertainties.

Treatment of Rotational Variations Caused by Solid Earth and Ocean Tides

Before combining the BIH optical astrometric series with the previously adjusted space-geodetic series comprising *SPACE94 [Gross,* op. cit., 1995], leap seconds were removed, and the effect of solid Earth tides upon the BIH UT1 measurements was removed by using the model of *Yoder et al. [1981].* Also, the model of *Dickman [1993]* was used to remove the effect upon UT1 of the ocean tides at the *Mf*, *Mf'*, Mm, and *Ssa* tidal frequencies (the *Dickman [1993]* oceanic corrections to the *Yoder et al.* [1981] results were actually removed). Since the BIH UT1 measurements represent an average value over a 5-day-long observation window, and since 5 days is a substantial fraction of the period of the fortnightly and monthly tides, the amplitudes of these tidal terms were attenuated prior to their removal from the BIH UT1 measurements. The attenuation factor that was applied to the amplitude of each fortnightly and monthly tidal term is a function of both the averaging interval (5 days) as well as the period of the individual tidal term [e.g., *Guinot*, 1970] and was about 0.80 for a fortnightly tidal term of period 14 days, and about 0.96 for a monthly tidal term of period 30 days, The amplitudes of the longer period (semiannual and longer) tidally induced rotational variations were not attenuated prior to their removal from the BIH UT 1 measurements.

Adjustments Made to the BIH Series

Prior to combining the BIH optical astrometric series with the space-geodetic series comprising SPACE94, corrections were made to its bias, rate, and annual term, and the stated uncertainties of the BIH measurements were adjusted by multiplying them by scale factors. First, the measurement uncertainties were adjusted by determining and applying scale factors that made each component of the residual series, obtained upon fitting a bias, rate and annual term to the difference of the BIH series with SPACE94, have a reduced chi-square of one. During this comparison for determining the measurement uncertainty scale factors, five outlying data points (those whose residual values were greater than three times their adjusted uncertainties) were deleted, The measurement uncertainty scale factors thus determined for the BIH series are given in Table 1.

After adjusting the measurement uncertainties, corrections to the bias, rate, and annual term of the B] H series were determined by comparing the BIH series to two different reference series: (1) the adjusted McDonald lunar laser ranging series that was incorporated into SPACE94, consisting of values for UTO and the variation of latitude (VOL) at the McDonald station, was used as a reference series to determine bias-rate and annual teri n corrections for these two components of the BIH series (i.e., the McDonald UTO and VOL components), and (2) SPACE94 was used as a reference series to determine the bias-rate and annual term corrections to the third orthogonal BIH component that is not determinable from single station lunar laser ranging observations. The advantage of using the adjusted McDonald LLR series for the purpose of determining corrections to the BIH series is that the McDonald LLR series spans 1970--1994 whereas SPACE94 spans onl y 1976–1 994. Thus, more reliable determinations of the needed B] H corrections can be made using the adjusted McDonald LLR series as a reference than can be done using SPACE94 because the interval of overlap between the BIH series and the McDonald LLR series is greater than it is with SPACE94. Note that the annual term of the BIH series was corrected, in addition to its bias and rate, because optical astrometric observations are known to be susceptible to seasonally varying systematic errors.

The bias, rate, and annual term corrections to tile BIH series were determined by: (1) transforming the BIH polar motion and UT 1 components to the McDonald UTO, VOL, and indeterminable components, (2) comparing these transformed B] H components to the adjusted McDonald LLR series (for the UTO and VOL components) and to the similarly transformed SPACE94 series (for the indeterminable component), and (3) transforming the corrections thus determined back to the usual UTPM (PMX, PMY, UT 1) frame. The bias, rate, and annual term corrections thus determined for the BIH series are given in Tables 1 and 2 in the UTPM frame. The errors in the bias, rate and annual term corrections (given in parentheses in Tables 1 and 2) are the formal errors in determining these corrections in the McDonald UTO, VOL, indeterminable frame, but arc given in Tables 1 and 2 after their transformation back to the usual UTPM frame.

COMB94

The BIH series was then combined with the adjusted space-geodetic series comprising SPACE94 after applying to it the corrections for bias, rate, annual term, and measurement uncertainty given in Tables 1 and 2. The resulting combination, spanning January 20.0, 1962 to January 27.0, 1995, is designated COMB94 and consists of values at 5-day intervals of PMX, PMY, and UT1–UTC (Figure 1), their 1-sigma forma] uncertainties (Figure 2), and correlations. Leap seconds were restored to the UT1 component, and the model of *Yoder* et *al. [1981]* was used to add back the effect of the solid Earth tides upon UT1 (the full amplitude, with no terms being attenuated, of the tidal effect at the epoch of the time tag was added back), and the model of *Dickman [1993]* was used to add back the ocean t idal corrections to the *Yoder et al. [1981*] model at the *Mf*, *Mf'*, *Mm*, and *Ssa* tidal frequencies. No diurnal or semi-diurnal ocean tidal terms were added back.

GENERATION OF POLE94

No optical astrometric observations made at the stations of the International Latitude Service were. used in creating the particular BIH series that was used above in generating COMB94 *[Li, 1985; Li and Feissel, 1986].* The ILS polar motion measurements, which are based solely upon latitude observations made at the ILS stations, are therefore independent of those comprising COMB94 and have been subsequently combined with them to form POLE94. Being based solely upon latitude observations, the ILS series contains no UT1 measurements but consists solely of polar motion measurements spanning 1899.8–1979.0 at monthly intervals. Although no uncertainties are given with the individual polar motion values, the precision with which they have been determined is estimated to be 10-20 mas [*Yumi and Yokoyama*, *1980,* p. 27]. An initial uncertainty of 15 mas was therefore assigned to each of the ILS polar motion values. Since this assigned measurement uncertainty will be adjusted later, its initial value is arbitrary, so long as it is not zero, and serves merely as an a priori estimate for the series adjustment procedure described below.

The lLS series was combined with COMB94 to form POLE94 after first: (1) correcting the ILS series to have the same bias, rate, and annual term as COMB94, (2) applying a constant multiplicative scale factor to the measurement uncertainties of the 11 .S series so that its residual, when difference with COMB94, had a reduced chi-square of one, and (3) deleting those data points whose residual values were greater than three times their adjusted uncertainties. These adjustments were determined separately for the x- and y-components of the ILS polar motion series by fitting a bias, rate, and annual term to the difference of the 11.S series with COMB94. The measurement uncertainties of the ILS polar motion values were adjusted by determining and applying a scale factor that made the residual of this fit have a reduced chi-square of one. During this procedure to determine uncertainty scale factors and bias, rate, and annual term corrections, three outlying ILS data points (those whose residual values were greater than three times their adjusted uncertainties) were deleted. Tables 1 and 2 give the values of the corrections thus determined and applied to the ILS series, with the formal uncertainties (1 sigma) in their determination being given in parentheses.

The result of combining the corrected ILS optical astrometric polar motion measurements with COMB94 is designated POLE94, spans January 20, 1900 to January 21, 1995, and consists of values at 30.4375-day intervals of PMX and PMY (Figure 3), their 1-sigma formal uncertainties (Figure 4), and correlations.

DISCUSSION AND AVAILABILITY

Since a Kalman filter was used in generating COMB94 and POLE94, the resulting polar motion and UT1 values (Figures 1 and 3) are smoothed to a degree depending upon both the spacing between the measurements being combined and the uncertainties that have been assigned to them. Since Earth orientation measurements determined by space-geodetic observing systems are more accurate (and have correspondingly smaller uncertainties) than are those made by optical astrometry, the degree of smoothing applied to those COMB94 and POLE94 Earth orientation values that are based upon optical astrometric observations is greater than that applied to those based upon the more recent space-geodetic observations,

COMB94 and POLE94 are available upon request either from the author or from NASA's Crustal Dynamics Data Information System (CDDIS). ASCII versions of these files are available from the CDDIS either by: (1) anonymous ftp to the internet address CDDIS.GSFC.NASA. GOV (128. 183.10.141) where they can be found in the 1994 subdirectory of the JPL directory, or (2) sending requests to Ms. Carey Nell, Manager, CDDIS, NASA/Goddard Space Flight Center, Code 920.1, Greenbelt, Maryland 20771, USA; telephone: (301) 286-9283; facsimile: (301) 286-0213; internet: noll@cddis.gsfc. nasa.gov.

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FIGURE CAPTIONS

Fig. 1. Plots of the x-component of polar motion (a), the y-component of polar motion (b), and UT 1 –UTC (c) from the combined Earth orientation series COM B94. COMB94 is a series of smoothed, interpolated polar motion and UT1-UTC values spanning January 20.0, 1962 to January 27.0, 1995 at 5-day intervals. The occurrence of leap seconds in the UT 1 -UTC component (c) is readily apparent, Prior to the introduction of leap seconds in 1972, Coordinated Universal Time (UTC) was adjusted by introducing step and rate changes designed to keep it close to UT1 [e.g., *Feissel and Essaïfi, 1994,* Table 1-3], the effect of which is also readily apparent in (c),

Fig. 2. Plots of the 1-sigma formal uncertainties in the determination of the x-component of polar motion (a), the y-component of polar motion (b), and UT1- -UTC (c) from COMB94.

Fig. 3. Plots of the x-component of polar motion (a), and the y-component of polar motion (b) from the combined Earth orientation series POLE94. POL1 :94 is a series of smoothed, interpolated polar motion values spanning January 20, 1900 to January 21, 1995 at 30,4375-day intervals.

Fig. 4. Plots of the 1-sigma formal uncertainties in the determination of the x-component of polar motion (a), and the y-component of polar motion (b) from POLE94. In deriving POLE94, a constant uncertainty was assigned to the ILS polar motion measurements, resulting in a constant uncertainty for the POLE94 polar motion values prior to the incorporation into POLE94 of the BIH Earth orientation series starting in 1962.

TABLE 1. ADJUSTMENTS TO BIAS, RATE, AND UNCERTAINTY

DATA SET NAME	BIAS (mas)			RATE (mas/yr)			UNCERTAINTY SCALE FACTOR		
BIH	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
	7.993	6.035	35.094	1.030	0.414	5.251	1.830	1.601	1.865
	(4.280)	(1.893)	(2.937)	(0.483)	(0.180)	(0.31.6			
ILS	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
	-49.540	7.389	---	0.053	-0.876	----	1.999	1.599	---
	(2.177)	1.747)		(0.444)	(0.356)				

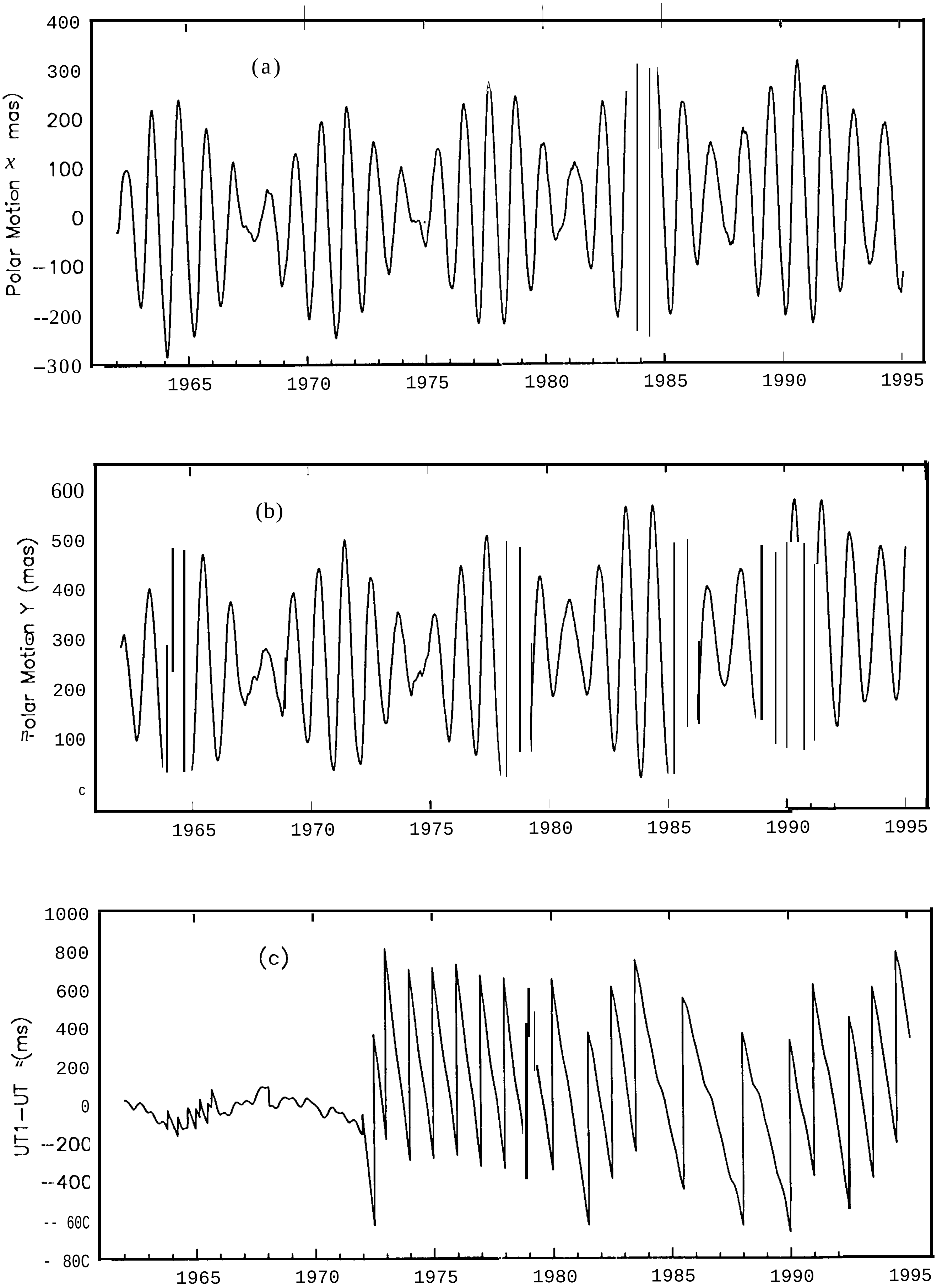
Reference date for rate adjustment of BIH series is 1988.0
Reference date for rate adjustment of ILS series is 1970.0

TABLE 2. ADJUSTMENT TO ANNUAL TERM

DATA SET NAME	COEFFICIENT OF SINE TERM (mas)			COEFFICIENT OF COSINE TERM (mas)		
	PMX	PMY	UT1	PMX	PMY	UT1
BIH	-5.627	-6.749	5.322	-2. "/99	9.824	-0.922
	(1.017)	(0.621)	(0. "181)	(1.069)	(0.683)	(0.832)
	PMX	PMY	UT1	PMX	PMY	UT1
I LS	-0.406	8.055	---	10.036	-10.922	---
	(3.059)	(2.453)		(3.063)	(2.457)	

Reference date for adjustment of BIH series is 1988.0
Reference date for adjustment of ILS series is 1970.0

A COMBINED EOP SERIES: COMB94



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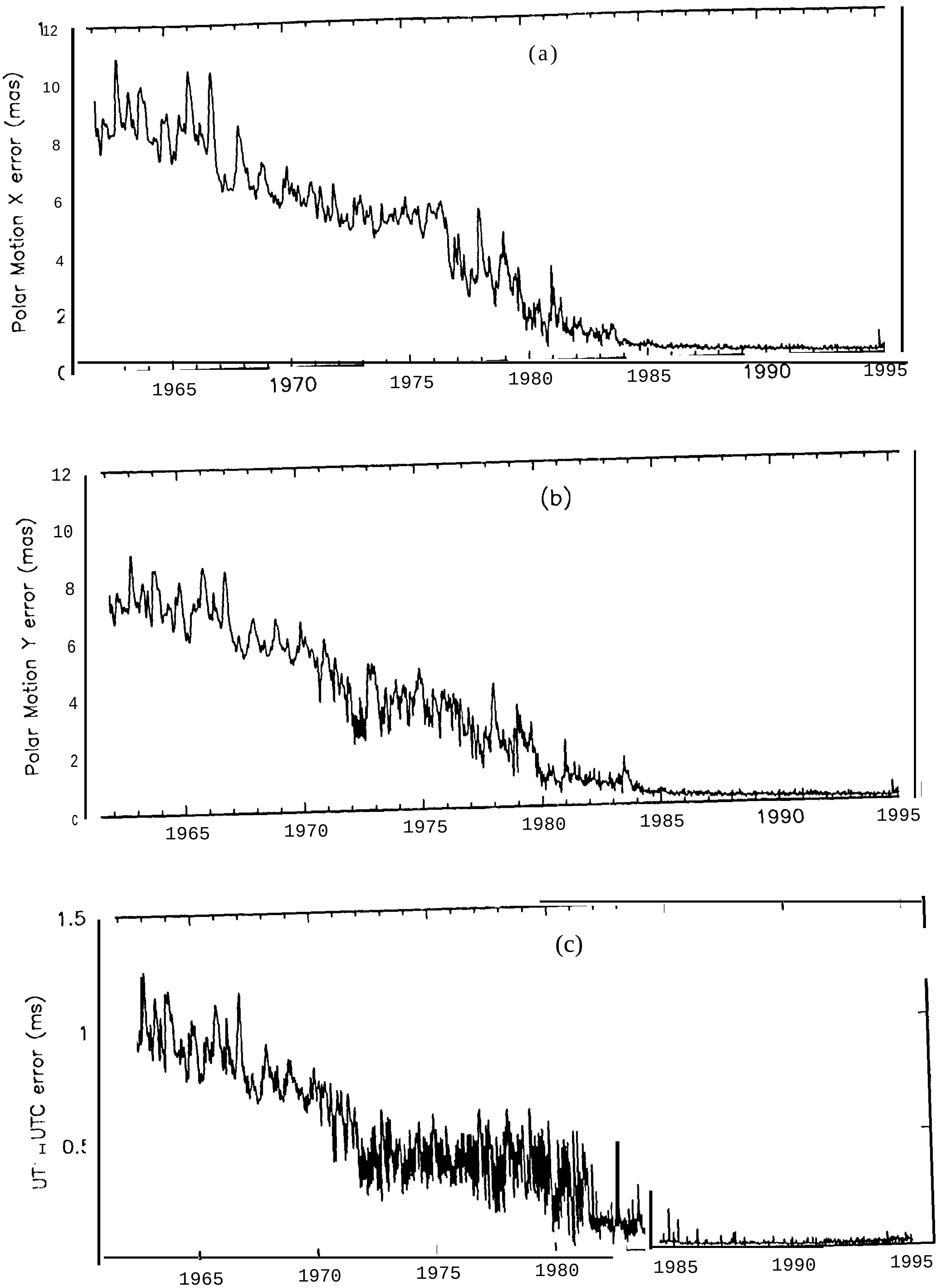

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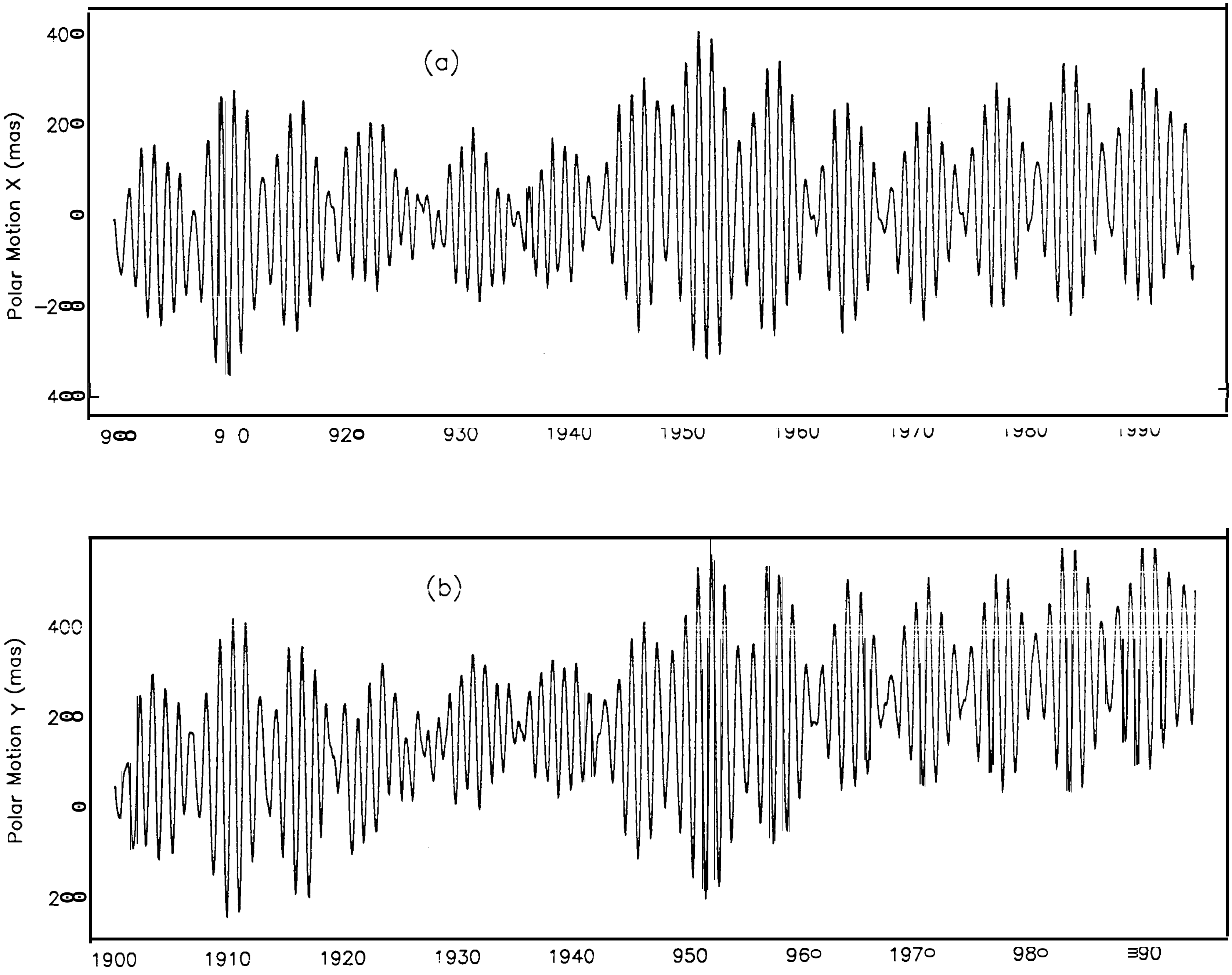

A COMBINED EARTH ORIENTATION SERIES: POL94